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FEASIBILITY STUDY FOR REMOTE DEBRIS SENSOR

FINAL REPORT

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millimeter wavelength can propagate through this nuclear debris cloud; ~~that~~ there is enough backscatter for detection; and ~~that~~ the location, particle size, and density be determined.

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1. Detection
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16. Laser Ranging
17. Scatter of Laser Light
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ABSTRACT

An analytical study was performed to determine if a millimeter wavelength radar system has the capability to remotely sense the dust distribution following a nuclear surface burst. In particular, could the density of particles greater than a given size be determined? Also, the typical laser wavelength of 1.06 μm was considered as a candidate. The study considered three problems: 1) the characteristics of the dust distribution function as cloud density changed in time, 2) the extinct coefficient as a function of wavelength and time/density for the dust cloud, and 3) the backscatter cross section as a function of wavelength and time/density. This information allowed one to determine if the millimeter wave system can sample a reasonable volume of the dust cloud, and how sensitive this technique is to variations in the distribution of dust sizes with time. These calculations showed that electromagnetic (EM) radiation of millimeter wavelength can propagate through this nuclear debris cloud, that there is enough backscatter for detection, and that the location, particle size, and density can be determined.

INTRODUCTION

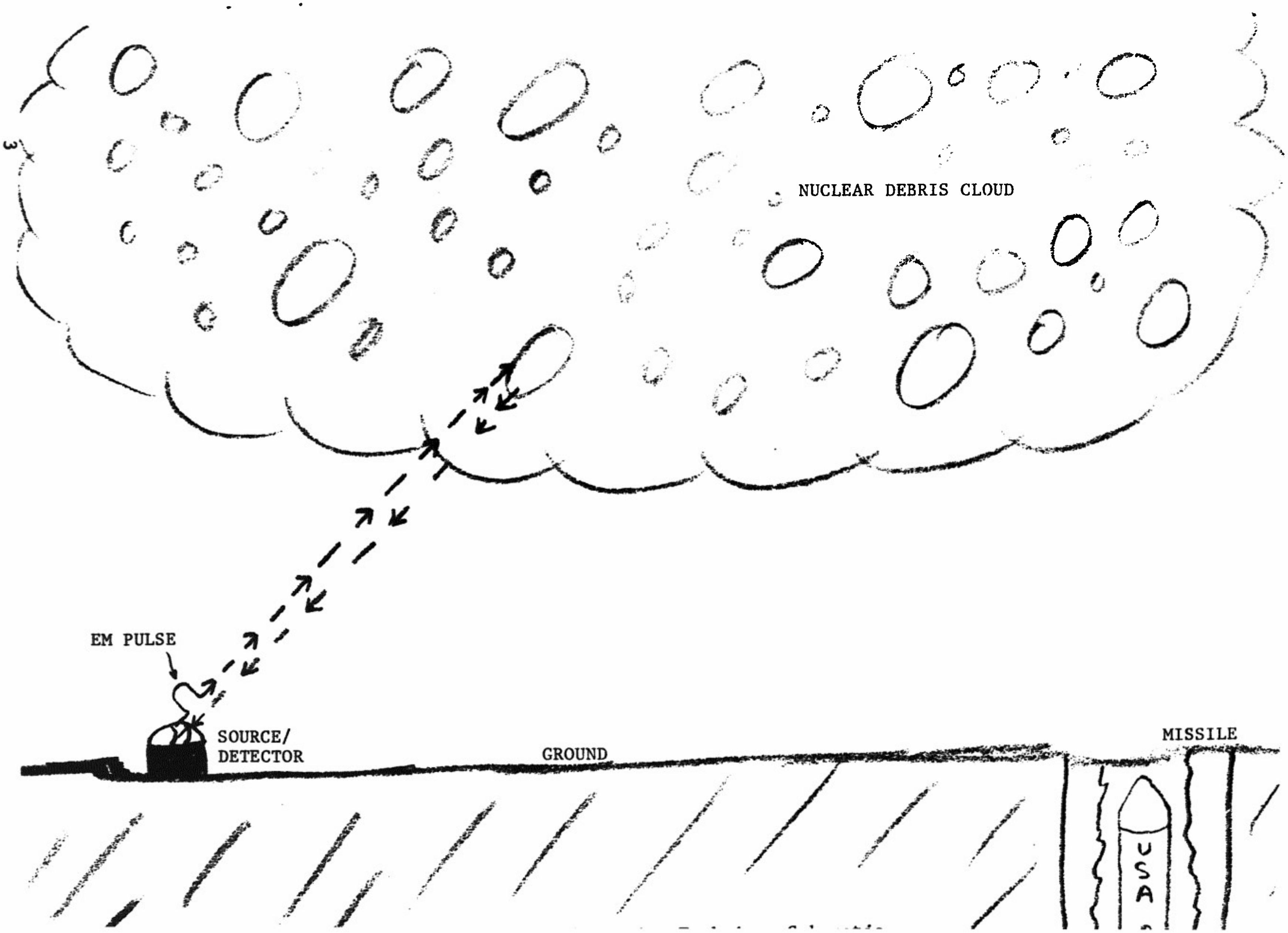
Following a surface nuclear detonation, there is considerable debris carried aloft. This debris is of concern if a missile silo has been attacked and the missile has to fly through this debris. In order to determine if a missile could safely fly through this debris, it is necessary to know something about the size, number of, and location of the particles. The purpose of this study is to determine if a millimeter wavelength radar system has the capability to remotely sense the dust distribution function for "dust" particles greater than a given size. Also, the typical laser wavelength of 1.06 μm was considered as a candidate. This study considers three problems: (1) the characteristics of the dust distribution function as cloud density changes in time, (2) the extinction coefficient as a function of wavelength and time/density for the dust cloud itself, and (3) the backscatter cross section as a function of wavelength and time/density. This information enables one to determine if the millimeter wave system can sample a reasonable volume of the dust cloud, and how sensitive this technique is to variations in the distribution of dust sizes with times. These calculations show that electromagnetic (EM) radiation of millimeter wavelength can propagate through the debris cloud, that there is enough backscatter for detection, and that the location, particle size, and density can be determined.

SENSING TECHNIQUE

The general technique is depicted in Figure 1. A pulse of electromagnetic (EM) radiation is directed towards the region to be remotely sensed. The location of the particle can be determined by the standard techniques by knowing the elapsed time between the initial pulse and the return scattered signal. Information on particle size is also possible from the return signal. This study showed it was possible to select wavelengths so that nearly 100 percent of the scatter was from particles one wanted to detect. Thus, any scatter signifies the presence of these large particles.

BASIC REQUIREMENTS FOR A SENSOR

There are several general requirements for a detector to remotely detect particles in a debris cloud following a nuclear detonation. First, the detector must give information on particle size, the number of particles, and their location. The detector must be able to detect large particles even on the outer extremities of the cloud which means the EM radiation must be able to propagate through the debris cloud. The system should provide near real-time detection. For this type of system to work, the backscatter cross section must be large enough for detection and the predominant backscatter must be from the larger particles of interest. In addition, any detector system will have to withstand the nuclear environment to the same extent the missile can. The wavelengths being considered here are in the quasi-optics region which means a confocal lens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configuration is possible. This may allow for a smaller system that could be more easily put underground in hardening against the nuclear environment.

PARAMETERS

The parameters to be used in these calculations are the following:

Nuclear Yield:	1 MT surface burst
Time:	5 to 15 minutes after nuclear detonation
Distribution of Particle Size:[1]	From DICE-708 (See Table 1) [Worst case]
Density of Debris Cloud:	From 10^{-4} g/cm^3 to 10^{-8} g/cm^3
Specific Gravity of Particles:	2 g/cm^3
Index of Refraction[2]:	$n = 2.0 - i\ 0.035$
Maximum Debris Cloud Size:	26 km high and 30 km in diameter

Wavelengths:	Frequency, GHz	Wavelength
(All Atmospheric	283,000	1.06 μm
windows except	140	2.14 mm
1.06 μm)	95	3.16 mm
	35	8.57 mm
	17	17.6 mm
	10	30.0 mm

Table 1. Distribution Function for the Particles in the Nuclear Debris Cloud as a Function of Time (from DICE-708)

PARTICLE DIAMETER D, cm	DENSITY DISTRIBUTION n(D), cm^{-4} at t = 5 min	n(D), cm^{-4} at t = 10 min	n(D), cm^{-4} at t = 15 min
1.750000E-4	3.636814E8	2.246268E6	3.101989E5
3.250000E-4	6.280777E7	3.879303E5	5.357133E4
4.750000E-4	1.233288E7	7.617365E4	1.051922E4
6.250000E-4	3.915143E6	2.418177E4	3.339387E3
7.750000E-4	1.609547E6	9.941318E3	1.372849E3
9.250000E-4	7.786160E5	4.809099E3	6.641136E2
1.750000E-3	4.143468E4	2.559201E2	3.534135E1
3.250000E-3	6.280777E3	3.879303E1	5.357133E0
4.750000E-3	1.233288E3	7.617365E0	1.051922E0
6.250000E-3	3.915143E2	2.418177E0	3.339387E-1
7.750000E-3	1.609547E2	9.941318E-1	1.372849E-1
9.250000E-3	7.786160E1	4.809099E-1	6.641136E-2
1.750000E-2	4.143468E0	2.559201E-2	3.534135E-3
3.250000E-2	6.280777E-1	3.879303E-3	5.357133E-4
4.750000E-2	1.233288E-1	7.617365E-4	1.051922E-4
6.250000E-2	2.144623E-1	1.259761E-3	1.730248E-4
7.750000E-2	1.047341E-1	6.140937E-4	8.432700E-5
9.250000E-2	5.066496E-2	2.970670E-4	4.079307E-5
1.750000E-1	2.696177E-3	1.580866E-5	2.170836E-6
3.250000E-1	4.086935E-4	2.396318E-6	3.290610E-7
4.750000E-1	8.025069E-5	4.705388E-7	6.461412E-8
6.250000E-1	2.547605E-5	1.493753E-7	5.932440E-9
7.750000E-1	1.047341E-5	6.140937E-8	1.061092E-9
9.250000E-1	5.066496E-6	2.970670E-8	5.133017E-10
1.750000E0	2.696177E-7	1.580866E-9	2.731577E-11
3.250000E0	4.086935E-8	7.134311E-11	8.931573E-13
4.750000E0	6.908604E-9	4.920349E-12	0.000000E0
6.250000E0	1.502405E-9	2.919425E-13	0.000000E0
7.750000E0	0.000000E0	0.000000E0	0.000000E0
9.250000E0	0.000000E0	0.000000E0	0.000000E0

CALCULATIONS

The computer code AGAUS was used for these calculations. This code was developed by the U.S. Army Atmospheric Sciences Laboratory, White Sands Missile Range. The code was made operational on the VAX here at the USAF Academy. The code uses Mie theory to calculate EM scattering and absorption of spherical particles. The code calculates the extinction and backscatter cross section as a function of particle size and wavelength. The code can weight these cross sections for most any distribution function. For analysis, it is useful to define several quantities the code calculates. Let n(D) dD be the distribution function defined as the number of particles per unit volume having diameters between D and D+dD. The code can integrate this distribution function to find the total number of particles. The quantities of interest are total number of particles per unit volume (N_0), number of particles greater than one millimeter (mm) in diameter per unit volume (N_1), and the number greater than five millimeters in diameter per unit volume (N_5). Analytically, these are expressed as:

$$N_0 = \int_0^\infty n(D)\, dD$$

$$N_1 = \int_{1\ \mathrm{mm}}^\infty n(D)\, dD$$

$$N_5 = \int_{5\ \mathrm{mm}}^\infty n(D)\, dD$$

The weighted cross sections needed are the cross section for particles greater than 1 mm in diameter (Σ_1), particles greater than 5 mm in diameter (Σ_5), and the average for all particles Σ_0. These are defined analytically as:

$$\Sigma_1(\lambda) = \int_{1\mathrm{mm}}^\infty \sigma(\lambda,D)\, n(D)\, dD$$

$$\Sigma_5(\lambda) = \int_{5\mathrm{mm}}^\infty \sigma(\lambda,D)\, n(D)\, dD$$

$$\Sigma_0(\lambda) = \int_0^\infty \sigma(\lambda,D)\, n(D)\, dD$$

where $\sigma(\lambda, D)$ is the probability of interaction per particle [units of cm^2] for a photon with wavelength λ with a particle of diameter D. The interaction talked about above is the one of interest, e.g., scatter, absorption.

From these weighted backscatter cross sections, it is possible to tell what fraction of the backscatter is due to particle size greater than 1 mm or 5 mm. This contribution is defined as the ratio of the respective cross section to the total cross section for all particles.

$$\frac{\Sigma_1(\lambda)}{\Sigma_0(\lambda)}$$ fraction of backscatter for particles greater than 1 mm.

$$\frac{\Sigma_5(\lambda)}{\Sigma_0(\lambda)}$$ fraction of backscatter for particles greater than 5 mm.

RESULTS OF CALCULATIONS

In analyzing these calculations, the following important questions will be addressed:

a. Will the EM pulse propagate to the outer extremities of the debris cloud?

b. What can be said about particle size?

c. Is the backscatter cross section large enough for detection?

d. Can the number of particles be determined?

In order to answer the first question, look at Table 2 where the extinction coefficients are tabulated. The reciprocal of the extinction coefficient is the mean free path (mfp) or the average distance between collisions. It may, therefore, be concluded that all wavelengths (except 1.06 μm) have the required cloud penetration at all times beyond 10 minutes. Shorter times favor the longer wavelength. A rough estimate of the effective penetration, remembering that the path is a two-way trip, might be when a photon's mean free path equals the cloud diameter (roughly 25 km). One thing becomes very clear, a 1.06 μm EM radiation would not work.

Table 2. Extinction Coefficients as Function of Time and Wavelength

FREQUENCY (GHz)	WAVELENGTH	TIME (Minutes)	EXTINCTION (km^{-1})	mfp* (km)
	1.06 μm	5	1.776×10^3	5.63×10^{-4}
		10	10.96	.091
		15	1.513	.661
140	2.14 mm	5	9.377	.107
		10	.0544	18.4
		15	.00652	153.4
95	3.16 mm	5	7.505	.133
		10	.0434	23.0
		15	.00498	200.8
35	8.57 mm	5	3.093	.323
		10	.0174	57.5
		15	.00115	869.6
17	17.6 mm	5	1.625	.615
		10	0.00865	115.6
		15	3.431×10^{-4}	2915.
10	30 mm	5	0.915	1.09
		10	.00421	237.5
		15	1.599×10^{-4}	6254.

* mfp = mean free path

The second question, on particle size, can be answered by looking at Table 3. By looking at the column listed percent contribution, it becomes clear that all the backscatter for wavelengths greater than 8.57 mm is due to particles greater than 1 mm in diameter. Thus, a return signal implies particles greater than 1 mm are present. Analogously, for particles greater than 5 mm in diameter, a wavelength of 30 mm or greater would be needed.

In order to answer the question of whether the backscatter cross section was large enough for detection, the signal to noise was calculated at 10 minutes after the nuclear detonation for a gated cell at the upper, outer extremities of the debris cloud (See Table 4). The signal was from a one KHz prf system summed over 1000 pulses. The signal is quite large and there should be no problem of detection. This large return implies that the backscatter cross section is indeed large enough for detection.

Table 3. Backscatter Cross Section as a Function of Wavelength, Particle Size, and Time. Also, the Fraction of Backscatter is given

λ	Time	BACKSCATTER X-SECTION [km^{-1}] Dust (All Particles)	Dust ($\geq$1 mm)	Dust ($\gtrsim$ 5 mm)	% CONTRIBUTION $\geq$ 1 mm Σ_1/Σ_0	% CONTRIBUTION $\geq$ 5 mm Σ_5/Σ_0
1.06 μm	5	4.25×10^2	1.25×10^{-1}	3.35×10^{-2}	.03	.008
	10	2.56	7.44×10^{-4}	1.79×10^{-4}	.03	.007
	15	3.54×10^{-1}	8.22×10^{-5}	4.78×10^{-6}	.02	.002
2.14 mm	5	1.46	8.76×10^{-1}	1.54×10^{-1}	60	10.5
	10	8.58×10^{-3}	5.53×10^{-3}	9.01×10^{-4}	64.4	10.5
	15	1.09×10^{-3}	6.76×10^{-4}	4.11×10^{-5}	62	3.8
3.16 mm	5	9.81×10^{-1}	8.13×10^{-1}	2.84×10^{-1}	82.9	30
	10	5.74×10^{-3}	4.42×10^{-3}	1.63×10^{-3}	77	28.4
	15	6.20×10^{-4}	4.39×10^{-4}	5.68×10^{-5}	70.8	10
8.57 mm	5	5.32×10^{-1}	5.27×10^{-1}	2.79×10^{-1}	99	52.4
	10	3.07×10^{-3}	3.04×10^{-3}	1.58×10^{-3}	99	51.5
	15	2.39×10^{-4}	2.35×10^{-4}	3.53×10^{-5}	98.3	14.8
17.6 mm	5	2.57×10^{-1}	2.57×10^{-1}	2.01×10^{-1}	100	77.8
	10	1.25×10^{-3}	1.24×10^{-3}	9.18×10^{-4}	99.2	73.4
	15	6.82×10^{-5}	6.80×10^{-5}	2.31×10^{-5}	99.7	33.8
30 mm	5	1.33×10^{-1}	1.33×10^{-1}	1.26×10^{-1}	100	94.7
	10	6.10×10^{-4}	6.09×10^{-4}	5.64×10^{-4}	99.8	92.5
	15	1.75×10^{-5}	1.75×10^{-5}	1.13×10^{-5}	100	[illegible]

Table 4. Signal to Noise Ratio for a Return at 10 Minutes. Signal at Outer Extremities of the Debris Cloud. The Detection Level is also Listed. These return signals were calculated by Dr. J. Gallagher of Georgia Tech using typical system parameters and cross sections calculated by this study. Also listed is the minimum signal needed for detection.

WAVELENGTH (mm)	DETECTION SIGNAL* (dB)	DETECTION LEVEL (dB)
8.57	36 (Coherent) 21	3
17.6	35.7 (Coherent) 17	3

* Gated Cell - 1000 pulses (1 sec)

Table 5. Information on Distribution Function (Number of Particles/cm^3)

	5 Min	10 Min	15 Min
N_0	2.44×10^5	1.374×10^3	1.897×10^2
N_1	6.75×10^{-4}	3.93×10^{-6}	5.32×10^{-7}
N_5	1.05×10^{-5}	6.15×10^{-8}	2.45×10^{-9}
N_1/N_0	3.04×10^{-9}	2.86×10^{-9}	2.81×10^{-9}
N_5/N_0	4.72×10^{-11}	4.48×10^{-11}	1.29×10^{-11}

In order to answer the last question on number of particles, it is necessary to look at what happens to the particle distribution with time. In Table 5, the total number of particles, the number of particles greater than 1 mm in diameter, and the number of particles greater than 5 mm in diameter per unit volume are given as a function of time. Also in Table 5 the ratio of the number of particles greater than 1 mm in diameter to the total number of particles and the number of particles greater than 5 mm in diameter to the total number of particles is given as a function of time. These ratios are interesting in that they are relatively constant over time. The ratio does drop off some at fifteen minutes. The fact that these ratios are relatively constant implies that the change in the distribution function is more of a dilution of particles rather than a drastic change in the relative shape of the distribution function. Actually, since the smaller particles do not contribute to the backscattered EM radiation, it is not important what happens with time to the shape of the distribution function for the smaller particles. It is only important, for the argument that follows, that the relative shape of the distribution function for larger particles remains relatively constant, i.e., the major change is from dilution for the larger particles. It is common and a good assumption that over a given particle size bin that the distribution function can be represented by

$$n(D,t) = a(t)D^{-4}$$

where D is the particle diameter and a(t) is density factor as function of time. Thus the particle distribution for particles greater than a certain size can be represented by this function. This representation is consistant with what Table 5 tells us and is the critical criteria needed to calculate the number of particles.

Since the major change in the distribution function is from dilution and since all the backscatter of EM radiation is from the larger particles, the backscatter cross section should be proportional to the number of particles. For example, by a least squares fit of Σ_1, vs. N_1 with time at $\lambda = 8.57$ mm gives:

$$\Sigma_1(\lambda) = 781\ N_1$$

or

$$N_1 = \Sigma_1(\lambda)/781$$

where Σ_1 is the backscatter cross section for particles greater than 1 mm in diameter and N_1 is the number of particles greater than 1 mm in diameter per unit volume and are the same quantities as previously defined. Thus, by knowing the magnitude of the return signal the backscatter cross section should be known and thus the number of particles greater than 1 mm (N_1) in diameter can be calculated by the above equation. In order to see how good the above equation is, the known scatter cross section $\Sigma_1(\lambda)$ can be used to calculate N_1, the number of particles greater than 1 m. Table 6 shows the comparison of actual values calculate values of N_1. The equation gives excellent results at early times, but deviates at 15 minutes. This deviation is due to the change in the distribution function at 15 minutes. Thus, by knowing the magnitude of the return signal the number of particles greater than 1 mm in diameter can be calculated. An analogous argument holds for particles greater than 5 mm in diameter for longer wavelengths.

Table 6. Comparison of Actual Particles Density to Calculated Density

TIME	Σ_1 [km^{-1}]	ACTUAL N_1 [#/cm^3]	CALCULATED N_1 [#/cm^3]	PERCENT DIFFERENCE
5	5.27×10^{-1}	6.75×10^{-4}	6.75×10^{-4}	0
10	3.04×10^{-3}	3.93×10^{-6}	3.89×10^{-6}	1
15	2.35×10^{-4}	5.32×10^{-7}	3.01×10^{-7}	43

ADVANTAGES OF DETECTION SCHEME

The single most important advantage of this system is that is is simple and requires a single radar system. The wavelength to use depends on the size of particles of interest. For this study it was assumed particles larger than two different sizes were of interest.

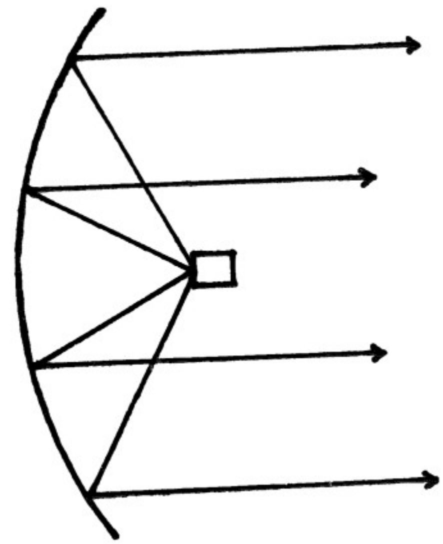
Coherent sources are possible at 8.57 mm and possible at 17.6 mm. Coherence reduces power requirements because the detection signal is proportional to the square of the sum of the electric fields. Also, at these wavelengths, the power requirements should be a minimum because the cross sections are larger than they would be at larger wavelengths.

Another advantage is that state-of-the-art components should be adequate. Table 7 lists typical system parameters that are available today for the wavelengths of interest.

Another possible advantage is that the wavelengths under consideration are in the quasi-optics region. This fact means a lens system is possible. See Figure 2. These lenses can be fabricated out of Rexalite which has excellent fabrication qualities. Some possible advantages of a lens system are that there is less antenna loss and the antenna is smaller. Since the antenna is smaller, it might be easier to put the system underground to harden the system against the nuclear environment.

Table 7. Typical System Parameters

WAVELENGTH	PEAK PULSED POWER	PULSE LENGTH	DETECTOR SENSITIVITY [dB]	ANTENNA GAIN [dB]
35 GHz (8.57 mm)	10 K Watts [Coherent]	50-200 ns [20 KHz Reprate]	3	30-50
17 GHz (17.6 mm)	50-100 K Watts and higher	50-200 ns	3	30-50
10 GHz (30 mm)	50-100 K Watts Possible 1 M Watt	50-200 ns	3	30-50



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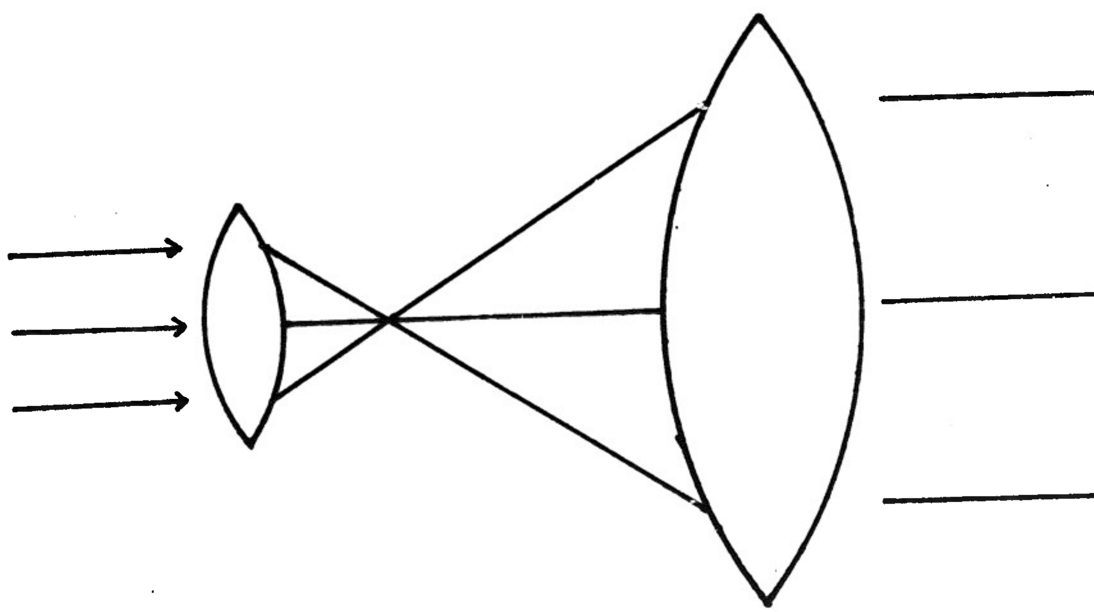

(b)

Figure 2. Illustrates a Typical Radar Antenna and a Lens System that is Possible in Quasi-Optics Region

SUMMARY

This study developed a technique of determining how soon after a nuclear detonation can a missile safely fly out. The remote sensing technique involves measuring particle density, size, and position with scattered EM radiation. It was concluded, by proper selection of the wavelengths of the EM radiation, that the radiation propogates through the cloud, that there is enough scatter from the larger particles of interest and that information on particle size and number is possible.

If the dust distribution is truly reflected by the calculations of the DICE or other related codes, a millimeter radar may provide easily the necessary data. If these codes do not reflect actual conditions, more analysis would be needed for specific distributions and operating characteristics.

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